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Plutonium, Nuclear Power, and Nuclear Weapons

A new fuel cycle architecture for nuclear power would expand its potential to contribute to the future global energy economy and reduce its potential nuclear weapon proliferation risks.

Although nuclear power generates a significant portion of the electricity consumed in the United States and several other major industrial nations without producing any air pollution or greenhouse gases, its future is a matter of debate. Even though increased use of nuclear power could help meet the energy needs of developing economies, alleviate some pressing environmental problems, and provide insurance against disruption of fossil fuel supplies, prospects for the expansion of nuclear power are clouded by problems inherent in some of its current technologies and practices as well as by public perception of its risks. One example is what to do with the nuclear waste remaining after electricity generation. The discharged fuel that remains is highly radioactive and contains plutonium, which can be used to generate electricity or to produce nuclear weapons. In unsettled geopolitical circumstances, incentives for nuclear weapons proliferation could rise and spread, and the nuclear power fuel cycle could become a tempting source of plutonium for weapons. At the moment, the perceived risks of nuclear power are outweighing the prospective benefits.

One reason for the impasse in nuclear development is that proponents and critics both appear to assume that nuclear technologies, practices, and institutions will over the long term continue to look much as they do today. In contrast, we propose a new nuclear fuel cycle architecture that consumes plutonium in a "once-through" process. Use of this architecture could extract much of the energy value of the plutonium in discharged fuel, reduce the proliferation risks of the nuclear power fuel cycle, and substantially ease final disposition of residual radioactive waste.

The current problem

Most of the world's 400-plus nuclear power reactors use lightly enriched uranium fuel. After it is partially fissioned to produce energy, the used fuel discharged from the reactor contains plutonium and other long-lived and highly radioactive isotopes. Early in the nuclear era, recovering the substantial energy value remaining in the discharged fuel seemed essential to fulfilling the promise of nuclear energy as an essentially unlimited energy source. A leading proposal was to separate the plutonium and

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reprocess it into new fuel for reactors that in turn would create, through "breeding," even more plutonium fuel. This would extend the world's resources of fissionable fuel almost indefinitely. The remaining high-level radioactive waste—stripped of plutonium and uranium—would be permanently isolated in geologic repositories. It was widely assumed that this "closed cycle" architecture would be implemented everywhere.

In 1977, the United States abandoned this plan for two reasons. Reduced projections of demand for nuclear power indicated no need to reprocess plutonium into new fuel for a long time to come, and it was feared that if the closed cycle were widely implemented, the separated plutonium could be stolen or diverted for use in nuclear weapons. Instead, the United States adopted a "once-through" or "open cycle" architecture: discharged fuel, including its plutonium and uranium, would be sent directly to permanent geologic repositories. As the world leader in nuclear power production, the United States urged other nations to adopt the same plan. Sweden and some other countries eventually did, but most countries still plan, or retain the option, to reprocess spent fuel.

Current practices, whether open or closed cycle, lead to continuing accumulation of discharged fuel, which is often stored at the reactor sites and rarely placed in geologic isolation or reprocessed to recover plutonium. This accumulation has occurred in the United States because development of a permanent repository has been long delayed. Where the closed cycle has been retained as an option, nations also continue to accumulate discharged fuel, because the low cost of fresh uranium fuel makes reprocessing uneconomical.

Most reprocessing work takes place in Europe. Recovered plutonium is combined with uranium into a mixed oxide (MOX) fuel, which is being used in some light water power reactors. (Also, significant quantities of plutonium separated from discharged fuel have been placed in long-term storage.) Prospects for future reprocessing, whether for MOX fuel for conventional reactors or for breeder reactors, depend on future demand for nuclear power and on the availability and cost of uranium fuel. Recent economic studies indicate that widespread breeder implementation is not likely to occur until well past the middle of the 21st century.

Thus, discharged fuel and its plutonium will continue to accumulate. The current global inventory of plutonium in discharged fuel is about 1,000 metric tons. Various projections indicate that by 2030, the inventory could increase to 5,000 metric tons if nuclear power becomes widely used in developing countries. Even if global nuclear power generation remains at present levels, the plutonium accumulation by 2030 will total 3,000 metric tons.

The plutonium in discharged fuel is a central concern for two reasons. First, plutonium's 24,000 year half-life and the need to manage nuclear criticality and heat produced by radioactive decay impose stringent long-term design requirements that affect the cost and siting of waste repositories. Furthermore, designing repositories to be safe for such a long time entails seemingly endless "what if" analysis, which complicates both design and the politics of siting

The second concern is the proliferation risk of plutonium. Plutonium at work in a reactor or present in freshly discharged fuel is in effect guarded by the intense radiation field that the fission products mixed with it produce. This "radiation barrier" increases the difficulty of stealing or diverting plutonium for use in weapons. The radioactive discharged fuel must be handled very carefully, with cumbersome equipment, and the plutonium must then be separated in special facilities in order to be fabricated into weapons. (Over several decades, as the radioactivity of the fission products decays, the radiation barrier is significantly reduced.) But plutonium already separated out of discharged fuel by reprocessing, and thus not protected by a radiation barrier, would be easier for terrorists or criminals to steal or for nations to divert for weapons.

This difference in ease of theft or diversion is one of many factors involved in assessing the proliferation risks of nuclear power. There are widely disparate views about these risks. Underlying the disparities often are differing assumptions about world security environments over the next century and the proliferation scenarios that might be associated with them. Such inherent unpredictabilities argue for creating new options for the nuclear power fuel cycle that would be robust over a wide range of possible futures.

A new plan

A better fuel cycle would fulfill several long-term goals by having the following features. It would greatly reduce inventories of discharged fuel while recovering a portion of their remaining energy value, keep as much plutonium as possible protected by a high radiation barrier during all fuel cycle operations, reduce the amount of plutonium in waste that must go to a geologic repository, and eventually reduce the global inventory of plutonium in all forms.

We propose a nuclear fuel cycle architecture that we believe can achieve these goals. It differs significantly from the current architecture in three ways.

Interim storage facilities. Facilities for consolidated, secure, interim storage of discharged fuel should be built in several locations around the world. The facilities would accept fuel newly discharged from reactors, as well as discharged fuel now stored at utilities, and store it for periods ranging from decades (at first) to a few years (later). These facilities could be similar to the Internationally Monitored Retrievable Storage System concept that is currently being discussed in the United States and elsewhere.

Plutonium conversion facilities. A facility of a new type—the Integrated Actinide Conversion System (IACS)—would process fuel discharged from power reactors into fresh fuel of a new type and use that fuel in its own fission system to generate electricity. Throughout this integrated process, the plutonium would be continuously guarded by a high radiation barrier. All discharged fuel that exists now or will exist—whether just generated, in the interim storage facilities, or in utility stockpiles—would eventually pass through an IACS. Each IACS could process fuel discharged from 5 to 10 power reactors on a steady basis. In comparison to a power reactor, an IACS would discharge waste that is smaller in volume and nearly free of plutonium. Although no such facility has yet been designed, several past and current R&D and demonstration prototypes could serve as starting points for its development.

The U.S. policy community will have to rethink its position on the risk/benefit balance of nuclear power

Waste repositories. The residual waste finally exiting an IACS would be ready for final disposal. Because it would be smaller in volume than the initial amount of fuel discharged from power reactors and have greatly reduced levels of plutonium and other long-lived isotopes, this waste could be deposited in permanent geologic repositories that could be less expensive than the repositories required for the current waste stream. There would also be greater confidence that the material could be isolated from the environment. Furthermore, because the material's radioactivity would decay in hundreds of years rather than thousands, a wider range of repository designs and sites could be considered.

In this architecture, most of the power will be generated by reactors whose designs will continue to be improved for safety and economical operation. These could evolve from current designs or they could be new. Some new designs, such as the high-temperature gas reactor, produce less plutonium that can be used for weapons in their operation. This could reduce the number of IACS needed for the fuel cycle architecture.

The safety and protection of discharged fuel, plutonium, and radioactive waste during transportation are important considerations in any fuel cycle. Quantities and distances of shipments of discharged fuel would be about the same in our architecture as in projections of current architectures. But in contrast to current approaches, when our architecture is fully implemented, all plutonium everywhere would always be protected by a high radiation barrier.

Together, consolidated interim storage facilities, transportation, IACS, and final waste repositories would constitute an integrated, international, fuel cycle management system. Individual facilities might be owned and operated by nations or by national or transnational companies, but the system as a whole would be managed and monitored internationally. Some new institutional arrangements would probably be needed, but some already exist, such as the International Atomic Energy Agency.

Although this new approach eventually reduces the global plutonium inventory, it allows for the introduction of breeder reactors in the distant future if world energy demand requires it.

Setting the timetable

The transition to our architecture

would extend over several decades (any significant change in the global fuel cycle would take this long). An immediate step would be to begin converting existing inventories of separated plutonium into MOX fuel for power reactors, continuing until all stores of separated plutonium have been eliminated. More capacity to fabricate MOX fuel would be needed. This conversion might take 30 years.

Construction of consolidated interim storage facilities could begin soon and be complete in 10 to 15 years. Development of IACS could also begin soon. Prototyping and pilot plant demonstration might require two decades. An additional two decades would probably be needed to build enough plant capacity to process accumulated inventories of discharged fuel. Later, IACS would keep pace with discharge so that only small inventories of discharged fuel would need to be kept at the interim storage sites.

As this strategy is implemented over several decades, global inventories of plutonium would decline several-fold instead of increasing as they would under current practices. All plutonium in the fuel cycle would be guarded by high radiation barriers, whether in power reactors, in consolidated interim storage, or in IACS conversion. Rather than facing the "plutonium economy" feared by analysts and policymakers worried about the proliferation of nuclear weapons, we would have created a "discharged fuel economy" that reduces the hazards of plutonium and improves the ability of nuclear power to contribute to the global energy economy. Later, nuclear power would be soundly positioned to make a possible further transition, perhaps to breeder reactors if needed, or to nuclear fusion.

Plutonium conversion is key

The linchpin of our strategy is the IACS. Although such plants are undoubtedly technically feasible, it will require substantial development to determine the most economical engineering approach. Their design is open territory for invention. Relevant R&D has been done in the past, and some is currently under way at modest levels in Japan and Russia. Twenty years of experience is available from the Argonne National Laboratory's 1970-1992 program to develop the Integral Fast Reactor. Recent work at Los Alamos National Laboratory to investigate the feasibility of nuclear systems designs that utilize intense particle accelerators offers other technology possibilities. Either approach could be an attractive foundation for IACS development. "Dry processing" of discharged reactor fuel in which no plutonium exists without a high inherent radiation barrier is being developed at the Argonne and Los Alamos National Laboratories as well as in Japan and Russia. Certainly, improving the efficiency of power reactors and creating designs that produce less plutonium would lower the burden on IACS facilities, so that one IACS plant could serve more than 5 to 10 power reactors. This would minimize the capital and operating costs of the IACS component of the new architecture.

The cost of our overall scheme is an important consideration. At issue are the costs of a consolidated interim storage system, additional MOX conversion systems to deal with current inventories of separated plutonium and the cost of adding the IACS step to the fuel cycle. Interim storage sites exist or are planned in several nations with nuclear power. (Even the United States, which subscribes to disposal of once-used fuel in a geologic repository, will probably require an interim storage facility until permanent disposition is available.)

Recent (though contested) estimates from the Organization for Economic Cooperation and Development indicate that the costs of the once-through and MOX fuel cycles might be roughly equivalent. Other estimates indicate that reprocessing and MOX fuel fabrication could add 10 to 20 percent to a nuclear utility's fuel cost. However, because fuel costs themselves typically account for only about 10 percent of the total electricity cost, the increase would be marginal.

The capital and operating costs for an IACS plant might be twice as much as for a standard power reactor because of the complexities in reprocessing and consuming plutonium. However, the cost of one IACS plant would be spread across the 5 to 10 power reactors it would serve, and its use could reduce costs incurred to store discharged fuel as well as costs associated with final geologic disposal of waste. The IACS would also create revenues from the electricity it generated.

Taking all these costs and savings into account, the effective cost increment for the entire fuel cycle could be on the order of 5 to 15 percent. This estimate, though uncertain, is within realistic estimates of future uncertainties in relative costs of nuclear and competing energy technologies—particularly when recovery of full life-cycle costs is taken into account.

Prospects

We are convinced that a new strategy is needed for managing the back end of the nuclear fuel cycle. The accumulation of plutonium-laden discharged fuel is likely to continue under current approaches, challenging materials and waste management and increasing the potential proliferation risk. We describe one particular alternative; there are others. What are their prospects?

It will be difficult to implement this or any new strategy for the fuel cycle. Market forces will not drive such changes. Governments, industries, and the various institutions of nuclear power will have to take concerted action. A change in the architecture of nuclear power of this magnitude will require sustained commitment based on workable international consensus among the parties involved. Most leaders in this arena understand that the back end of the nuclear fuel cycle needs to be fixed, but they disagree on why, how, and when. If this disagreement persists, it will seriously hinder the necessary collective action.

Stronger and more constructive U.S. engagement will be needed, but that is unlikely to happen, or would be futile if attempted, if U.S. policy continues to oppose any kind of reprocessing of discharged fuel. The U.S. policy community will have to rethink its position on the risk/benefit balance of nuclear power and its strategy for dealing with the proliferation risks of the global nuclear fuel cycle; the international nuclear power community will have to acknowledge that structural changes in the architecture of the fuel cycle are needed on broad prudential grounds.

It is beyond the scope of this article even to outline the details of what must be done to create the conditions necessary for the needed collective actions. A significant first step would be for the U.S. Department of Energy to adopt, as one of its important missions, development of a comprehensive long-term strategy for expanded international cooperation on global nuclear materials management, including technologies for new fuel cycle architectures. Of course, a lot more than that will be needed and none of it will be easy, but we believe it can be done. And now is the time to start.